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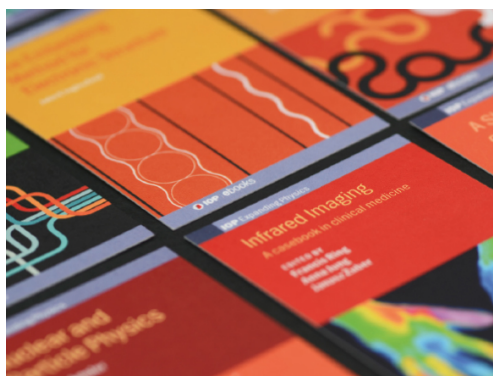
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Conceptual Study on lighter and more compact transmission cable systems for Hybrid Aircrafts

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Abstract. More electrically driven aircrafts with electric propulsion systems are supposed to require 1-40 MW. In order to realize such heavily electrical aircrafts the development of lighter and more compact transmission cable systems is indispensable. We compared metal cables and superconducting cables, and found that DC superconducting cables are lighter and more compact than metal cables at voltages as high as ± 6 kV.

1. Introduction

More electrically driven aircrafts with electric propulsion systems are supposed to require 1-40 MW. In order to realize such heavily electrical aircrafts, in addition to the development of higher voltage electrical systems with motors and generators with much higher power densities than those at present, compatible with low atmospheric pressure at a high altitude, the development of lighter and more compact transmission cable systems is also indispensable. ASCOT is studying superconducting cables for aircrafts, and in this paper we present the results of our feasibility study on superconducting cables for aircrafts.

2. Feasibility Study by following current AC system

As the initial step of this conceptual study, we performed feasibility study to compare metal cables and high temperature superconducting cables. First FS(Feasibility Study) is based on current 230 V AC system and an image of a hybrid aircraft used in our feasibility study is shown in figure 1.

Gas turbine and generator produce 3 phase 230 V AC, which is transmitted by 4 MW transmission cables to 8 motors of 4 MW output. We assumed, for takeoff and landing, the cables carry 100% current of 4 MW power and for cruising 33% current.

We chose cable specifications, as close as current operations. The specifications assumed are shown in table 1. Capacity is 4 MW per circuit. Voltage is 230 V AC line to line as determined by Paschen minimum voltage of 350 V for air [1]. Frequency is 400Hz as is commonly used in present aircrafts. For the application of superconductivity to transmission, DC is more appropriate. However, AC / DC convertor at present is very heavy to be used for on-board transmission. Current is



determined by power divided by, voltage multiplied by square root of 3. The length of the transmission line is assumed to be 50 m.

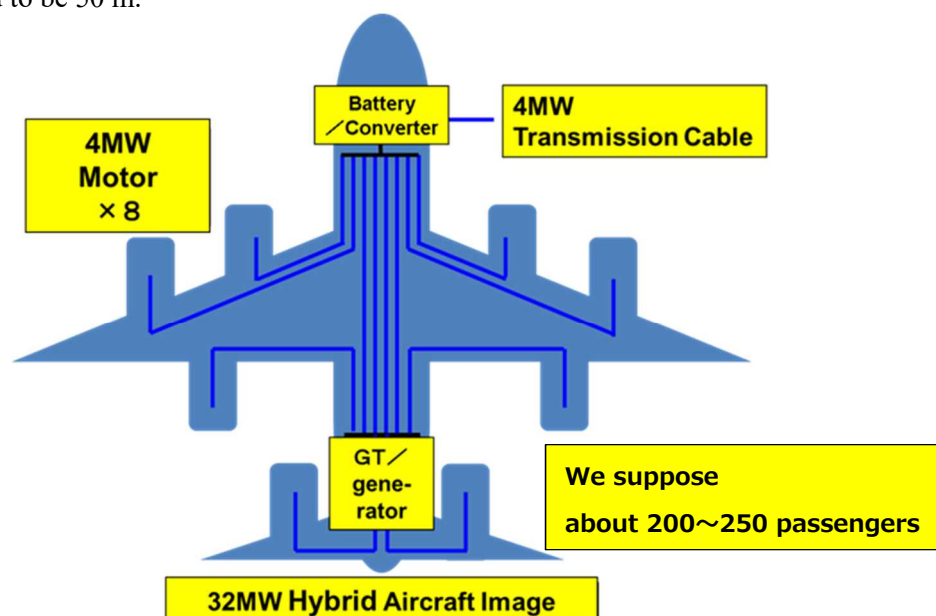


Figure 1. An image of a hybrid aircraft.

Table 1. Cable specifications assumed

capacity	voltage	frequency	current
4MW/cct	230V/Paschen minimum 350 V	400Hz/heavy DC/AC converter	10 kA
length	operation	cooling	
50 m	100% output for 1 hr., 33% for 23 hr.	no-onboard refrigerator	

During 30 min takeoff and 30 min landing, 100% output is assumed. During the cruising of the rest of 24 hours, 33% output is assumed. The refrigerator is heavy, so in this study, no on-board refrigerator is assumed. Sumitomo electric developed 3 phase superconducting cable using 2nd generation wires and tested in the testing field, in a Japanese government project [2]. The verification test and the cable are shown in figure 2 and figure 3. This might be an example for this aircraft cable.



Figure 2. 15m long cable verification system @SEI Feb. 2013[2]



Figure 3. AC Superconducting cable[2]

For a metal cable, we estimated it by following American standard(AS50881) and an example of Cu cable is shown in figure 4. The cable design is as follows.

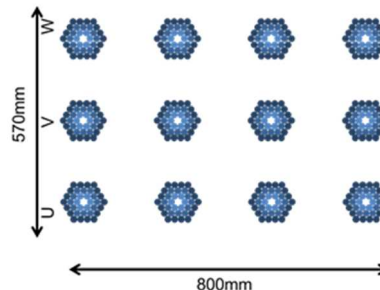


Figure 4. Cu cable example

Wire conductor is composed of 2590 strands. A bundle is composed of 36 wires. They are arranged separately with the separation of one diameter of the bundle. Wire conductor size is AWG 3/0 and wire diameter is 16.5 mm, whose current capacity at 170°C with the surrounding temperature of 100°C is 400 A, following the conditions shown in the reference [3].

Current capacity is reduced due to elevation to 83% at 45000 ft., and due to bundling to 27%, and due to multi bundling to 80%, and finally wire current capacity is 70.6 A. Cross section is 570 mm times 800 mm, and weight is 20.8 thousand kg for 50 m cable.

Next example is Al cable. Wire conductor is composed of 559 strands. A bundle is composed of 36 wires. And an example of Al cable is shown in figure 5. The cable design is as follows.

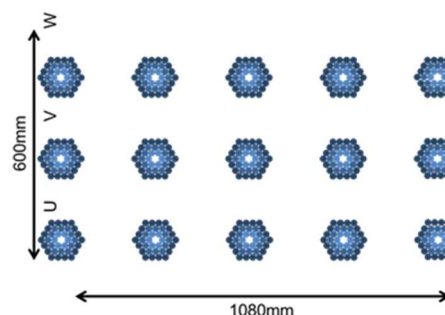


Figure 5. Al cable example

They are arranged separately with the separation of one diameter of the bundle. Wire conductor size is AWG 4/0 and wire diameter is 17.3 mm, whose current capacity at 170°C with the surrounding temperature of 100°C is 376 A.

Current capacity is reduced due to elevation to 83%, and due to bundling to 27%, and due to multi bundling to 68%, and finally wire current capacity is 56.4 A. Cross section is 600 mm times 1080 mm, and weight is 13 thousand kg for 50 m cable.

As for superconducting cable, we estimated 3 types of cable, such as cooled by solid nitrogen, liquid nitrogen with circulation and liquid nitrogen without circulation.

Figure 6 shows solid nitrogen type. On ground liquid nitrogen is poured and cooled by refrigerators or by other measures to, for example, 20K.

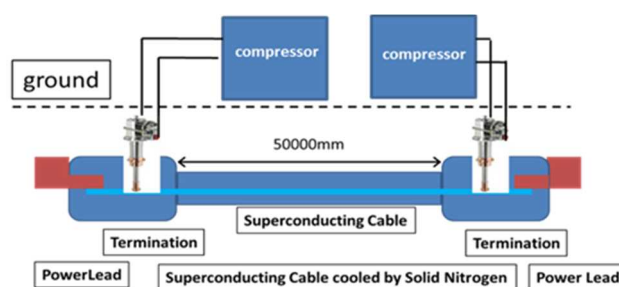


Figure 6. Solid nitrogen type

The cooling system will be removed before takeoff. Cable type is triad, in other words, 3 cores in one cryostat. The power lead is designed as conductively cooled. Maximum operating temperature is set to be 60K as an example. For faster cooling down, thermal conductors are installed in the cryostat. AC loss is assumed to be 1 W/m/p by using lot of wires.

Figure 7 shows a liquid nitrogen cooling type with circulation. The reservoir of liquid nitrogen can store liquid nitrogen consumed during a flight.

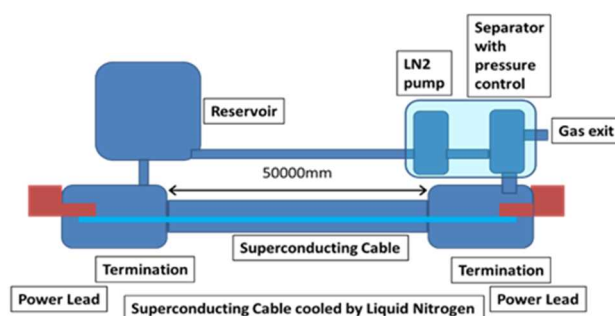


Figure 7. Liquid nitrogen cooling type with circulation

Thicker wall is used because the pressure of liquid nitrogen will be increased due to inclination of the aircraft. Gas nitrogen generated after cooling is moved by the pump to the separator which separates gas nitrogen from the liquid nitrogen and only the gas nitrogen is exhausted thanks to the pressure control.

The cable is assumed to be triad and the power lead is conductive cooling. AC loss is supposed to be 10 W by using a little bit fewer wires to reduce weight.

Figure 8 shows a liquid nitrogen cooling type without circulation. Liquid nitrogen to be consumed in a flight is poured into the cable and termination before takeoff.

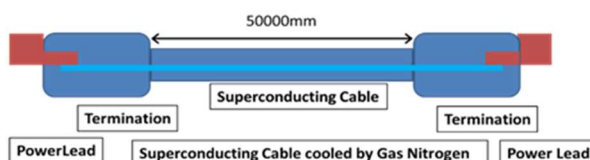


Figure 8. Liquid nitrogen cooling type without circulation

Liquid nitrogen inside is divided by separated rooms to avoid pressure accumulation and large dry area formation of the cable during inclination of the aircraft.

Gas nitrogen generated after cooling is exhausted from each room by a filter. The cable core has layers to increase thermal conductivity. Due to the temperature increase from the liquid nitrogen temperature, the AC loss increases a little bit.

Table 2 shows the comparison between solid, liquid with and without circulation, and Al and Cu cables.

Table 2. Results of FS on cables for 4 MW transmission

case	Solid	Liquid w/ circulation	Liquid w/o circulation	Al	Cu
Cable dia. (mm)	126	108	121	600×1080	570×800
50 m Cable weight (kg)	1020	760	1620	13000	20800
Termination L×dia (m)	1.2×1.8	1.2×0.5	1.2×0.9	-	-
Termination Weight (kg)	5180	840	1580	100	53
Reservoir L×dia (m)	-	2.20.9	-	-	-
Reservoir Weight (kg)	-	1260	-	-	-
Circulator Weight (kg)	-	560	-	-	-
Total weight (kg) (%)	6200 (30%)	3420 (16%)	3200 (15%)	13100 (63%)	20800 (100%)

Cable size and weight are the smallest when it is liquid cooling type with circulation. Termination size and weight are also the smallest in that case. However, this type requires reservoir, whose size and weight are large, and also requires circulator system including a pump, whose weight is not negligible.

Solid cooling type requires a lot of nitrogen, because the sensible heat is smaller compared to the latent heat.

At the bottom, total weights are compared, resulting in that the liquid cooling type with circulation is the lightest and weighs about 15% of the Cu cable.

However, each cable has merits and demerits, so in order to decide which type is the most suitable, more information about the specifications of the cable and layouts of the circuit are required. Some experimental study is also essential.

As the summary of this FS on 230V system, the superconducting cable cooled with liquid nitrogen without circulation is the lightest and the most compact cable for 4 MW capacity with 230 V AC between lines and 50 m length.

3. Feasibility Study with the voltage level of 1.5 kV

Larger transmission capacity as large as 40 MW will be required for the trunk line of wide body aircrafts. For that case, we studied higher voltage applications of ± 1.5 kV DC case, which means 1.5 kV line to the earth and 3 kV line to line, and 1.5 kV 3 phase AC case, which means 1.5 kV line to line. This study also turns out to be the comparison between DC and AC, because their current levels are close to each other. The configuration of DC superconducting cable is single concentric and that of AC superconducting cable is triad, which is 3 cores in one cryostat, as are shown in figure 9.

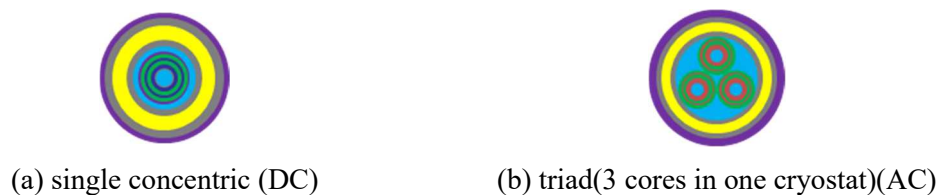


Figure 9. Configuration of superconducting cable

Table 3 shows the comparison between Al cable and superconducting cable for each case. Al cables are estimated by taking cable bending and reduction of current capacity due to multi bundling

into account. Superconducting cables are assumed to be cooled by liquid nitrogen without circulation, because it was found to be the lightest.

At the bottom, total weights of cable and termination are compared, resulting in that DC superconducting cable system is the lightest, and weighs about 8% compared to AC Al cable.

Table 3. FS for 40 MW power transmission with ± 1.5 kV DC and 1.5 kV 3 phase AC

40 MW system	± 1.5 kV DC		1.5 kV(L-L)3 phase AC	
Conductor	Al	SC	Al	SC
Current (A)	13300	133000	15400	15400
Cable dia. (mm)	190×1910 26 cols, 3 rows, (wire dia. 37.5 mm \times 39 pairs)	79 (single concentric)	600×1820 8 cols, 3 rows,(1 bundle = 17.3 mm dia. Wire \times 36)	146 (triad(3 cores in one cryostat))
50 m Cable Weight (kg)	10370	360	20880	2890
Termination L \times dia. (m)	-	1.2×0.9	-	1.2×1.1
Termination Weight (kg)	120	1390	250	2900
Total weight (kg) (%)	10490 (50%)	1750 (8%)	21130 (100%)	5800 (27%)

4. Feasibility Study with higher DC voltages

Because we found that DC is more suitable to reduce transmission system weight, and higher voltage results in lighter weight, we furthermore studied higher DC voltage application, whose voltages are ± 3 kV and ± 6 kV.

Table 4 is the comparison between Al cable and superconducting cable for each case.

At the bottom, total weights of cable and termination are compared, resulting in that DC superconducting cable system is lighter, even at the high voltage of ± 6 kV.

Table 4. FS for 40 MW power transmission with higher DC voltages

40 MW system	± 3 kV DC		± 6 kV DC	
Conductor	Al	SC	Al	SC
Current (A)	6700	6700	3300	3300
Cable dia. (mm)	110×1310 18 cols, 2 rows, (wire dia. 37.5 mm \times 18 pairs)	78 (single concentric)	110×710 10 cols, 2 rows, (wire dia. 37.5 mm \times 10 pairs)	80 (single concentric)
50 m Cable Weight (kg)	4720	330	2600	270
Termination L \times dia. (m)	-	1.2×0.9	-	1.2×0.5
Termination Weight (kg)	55	830	30	540
Total weight (kg)	4775	1160	2630	810

Figure 10 summarizes the FS of 40 MW DC high voltage cable. The ratio of superconducting cable weight divided by that of Al cable is 17% at ± 1.5 kV, 24% at ± 3 kV, and 31% at ± 6 kV.

Therefore, superconducting cable is very effective to reduce the transmission system weight up to very high voltage of ± 6 kV.

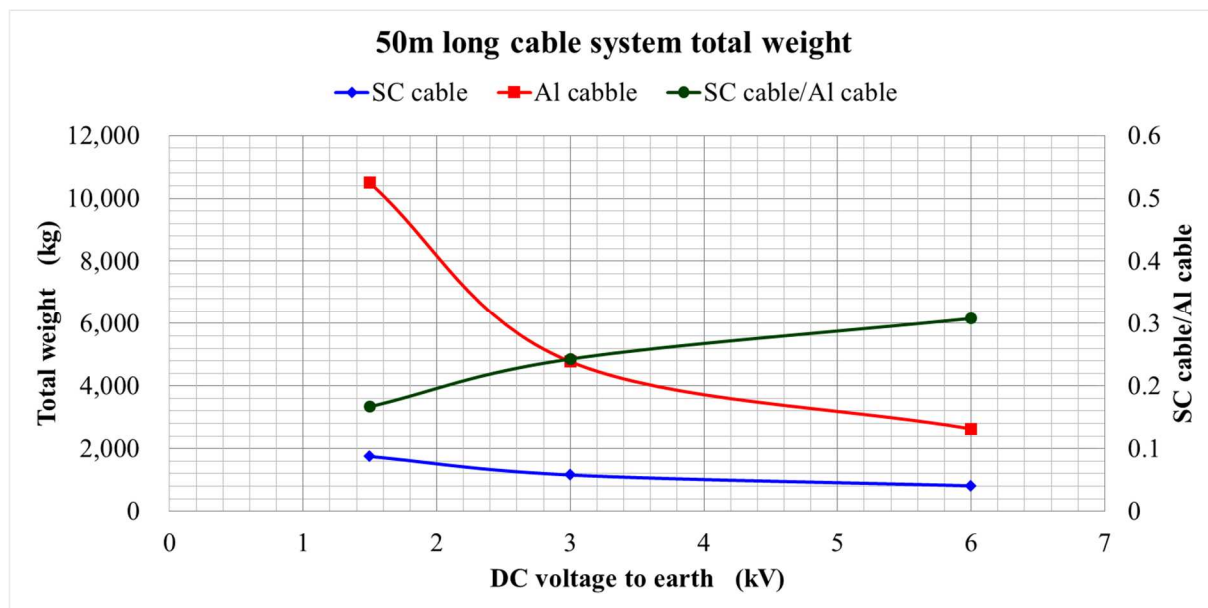


Figure 10. Weight of SC cable/weight of Al cable

5. Future Study

At present, electric power of 1 MW and voltage level of 230V AC are used in B787. However, future more electric aircrafts require 4 MW-40 MW, and application of higher voltages is contemplated.

As for future study, the first challenge is applying high voltage. From the Paschen's law, BD voltage is a function of P times d as is shown in figure 11. P is the pressure of air and d is the gap length between electrodes. When we use air for insulation, the minimum breakdown voltage is 350 V DC, which corresponds to 230 V AC.

For example, at 1bar and 2.5mm, the breakdown voltage is 9kV and at 100mbar and 2.5mm, the breakdown voltage is 1.6kV as is shown in figure 11. In other words, at low pressure of 100 mbar at the altitude of 23500 m, the BD voltage decreases to 1/5.6 of that at sea level. In order to keep the same BD voltage at 100mbar as that of at 1bar, gap must be increased by 10 times of that required at 1bar. Understanding the cable system BD voltage at unpressurized conditions is important.

For lighter cable system, the challenge in case of Al cable is to develop technology to cope with softness at high temperature and to allow light crimp joints. Al will creep at higher temperatures, which means it will be difficult to use it in wire with temperature ratings higher than 150 to 175 C. There are Al conductors used at present, but they are only used on certain portions of the aircraft.

Connectors for Al conductor are heavier than those used for plated copper, and this limits the weight advantage of Al conductor on aircraft to longer runs of wire. Application of Al cable to transmission trunk line in Hybrid Aircrafts requires lots to be developed.

As for superconducting cable, small bending radius and lighter weight are the challenges. Superconducting cable system has to be developed as part of hybrid aircrafts development.

As for future FS, cable system weights should be compared based on the configurations of grids in aircrafts, such as voltage, capacity, length, flight duration, cable branch etc.

For an example, transmission cable system weight is estimated with the cable length as a parameter, resulting in figure 12.

The weight ratio of superconducting cable weight divided by that of Al cable is less than one, when the cable length is longer than 10m. Even for shorter length than 10m, superconducting cable is beneficial, because the voltage of the cable can be lower than that of Al cable for the transmission of the same amount of power, and therefore it will be electrically more reliable.

Consequently superconducting cable system is expected to be beneficial for wide range of application.

Furthermore, the transmission cable system weight study should include the weight of power electronics.

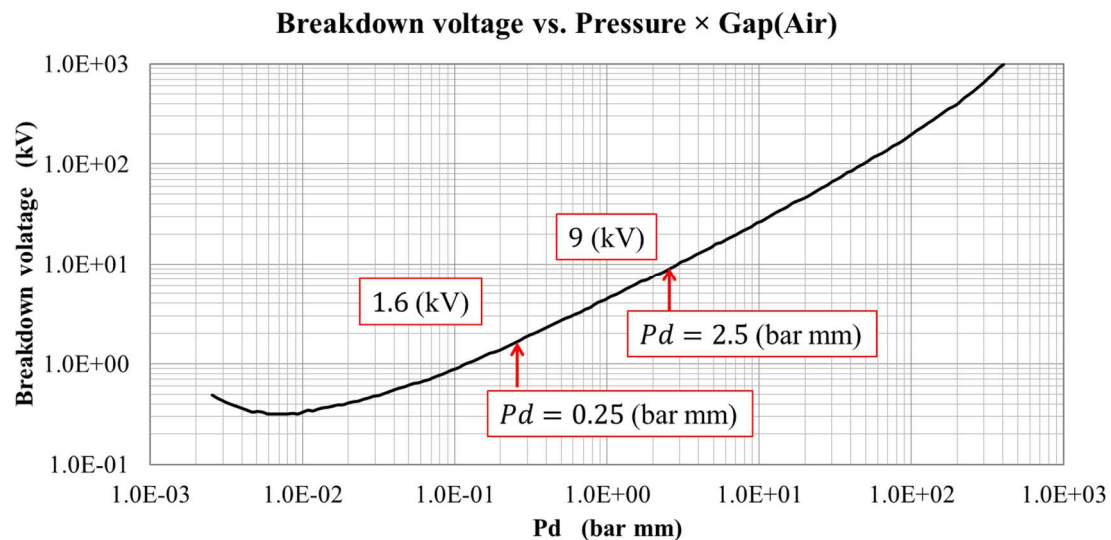


Figure 11. Paschen curve(Air)[1]

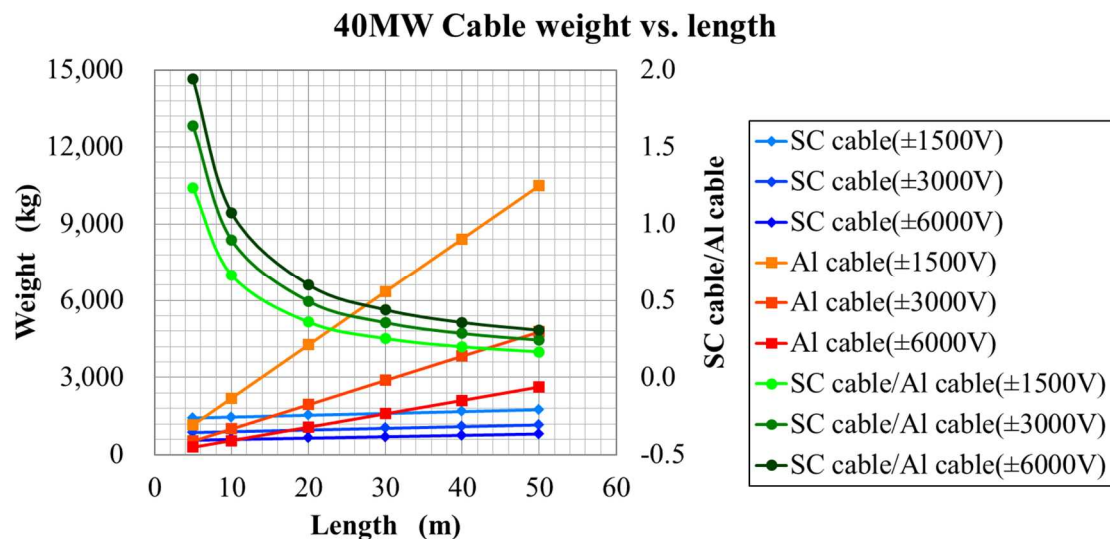


Figure 12. weight vs. length

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